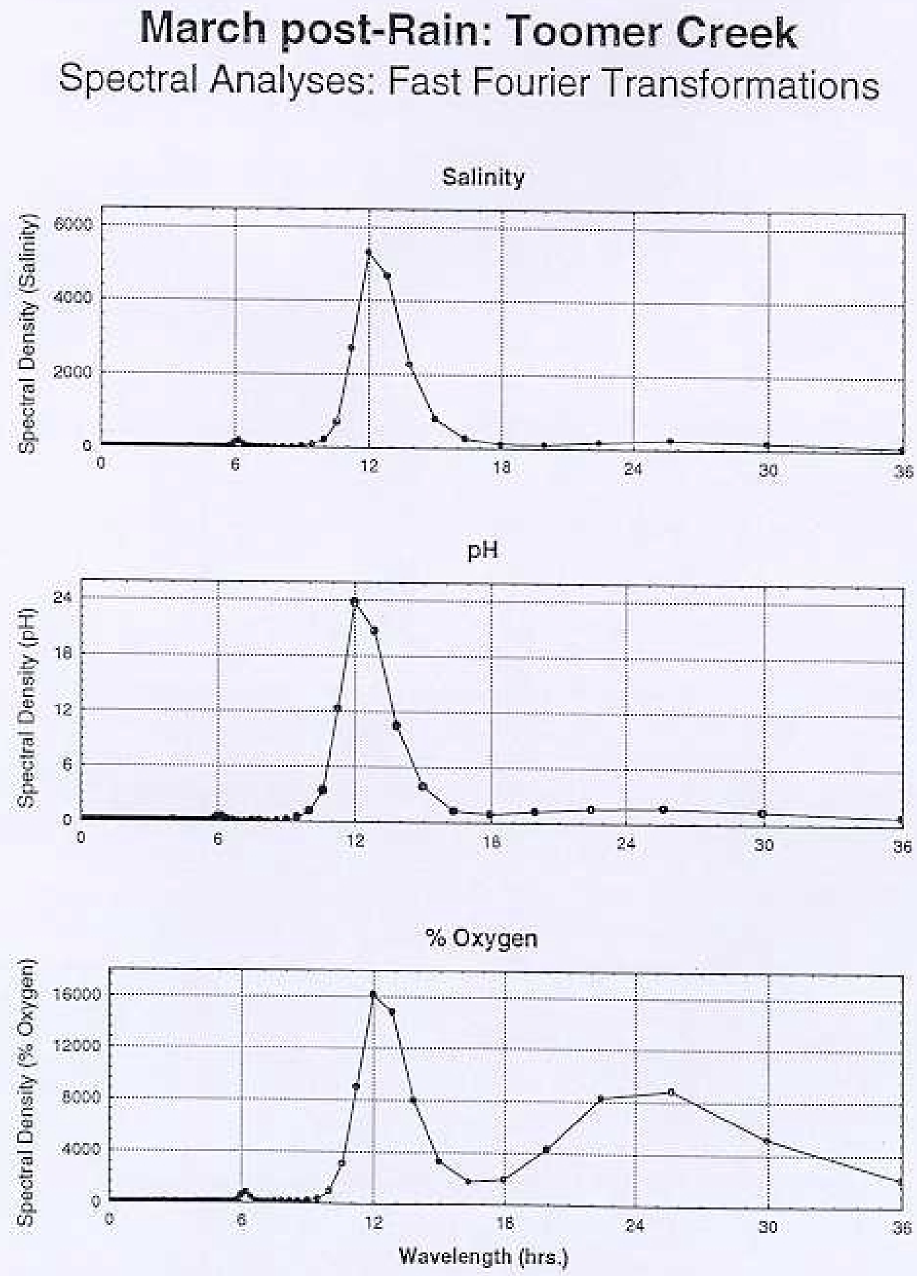


Figure 16.

Tropical Storm Jerry (James Island Creek).

The passage of Tropical Storm Jerry in 1995 after a relatively long period of drought afforded another glimpse into the dynamics of these estuarine creeks (Fig. 17). The prolonged drought before Tropical Storm Jerry's passage had the effect of dampening the variation in salinity (approx. 3 ppt range), presumably due to a lack of freshwater input during low tidal stages. The relationship between pH and salinity, and oxygen and salinity suggests that while oxygen and pH show a high degree of correlation in either drought or wet conditions, drought conditions seem to "collapse" the conservative aspect of the relationship with salinity (Fig. 18 and 19). As speculation, the input of groundwater may dilute the creek waters biomass on each tidal cycle, thus reducing the per unit respiration rate. During droughts freshwater input all but ceases and the relationship between respiration and salinity diminishes. Two days after the first rain, the oxygen content dropped by approximately 20% and stayed below pre-storm values for at least five or six days. Another rainstorm occured around day 243 which caused a further alteration in the pH and oxygen content signals.

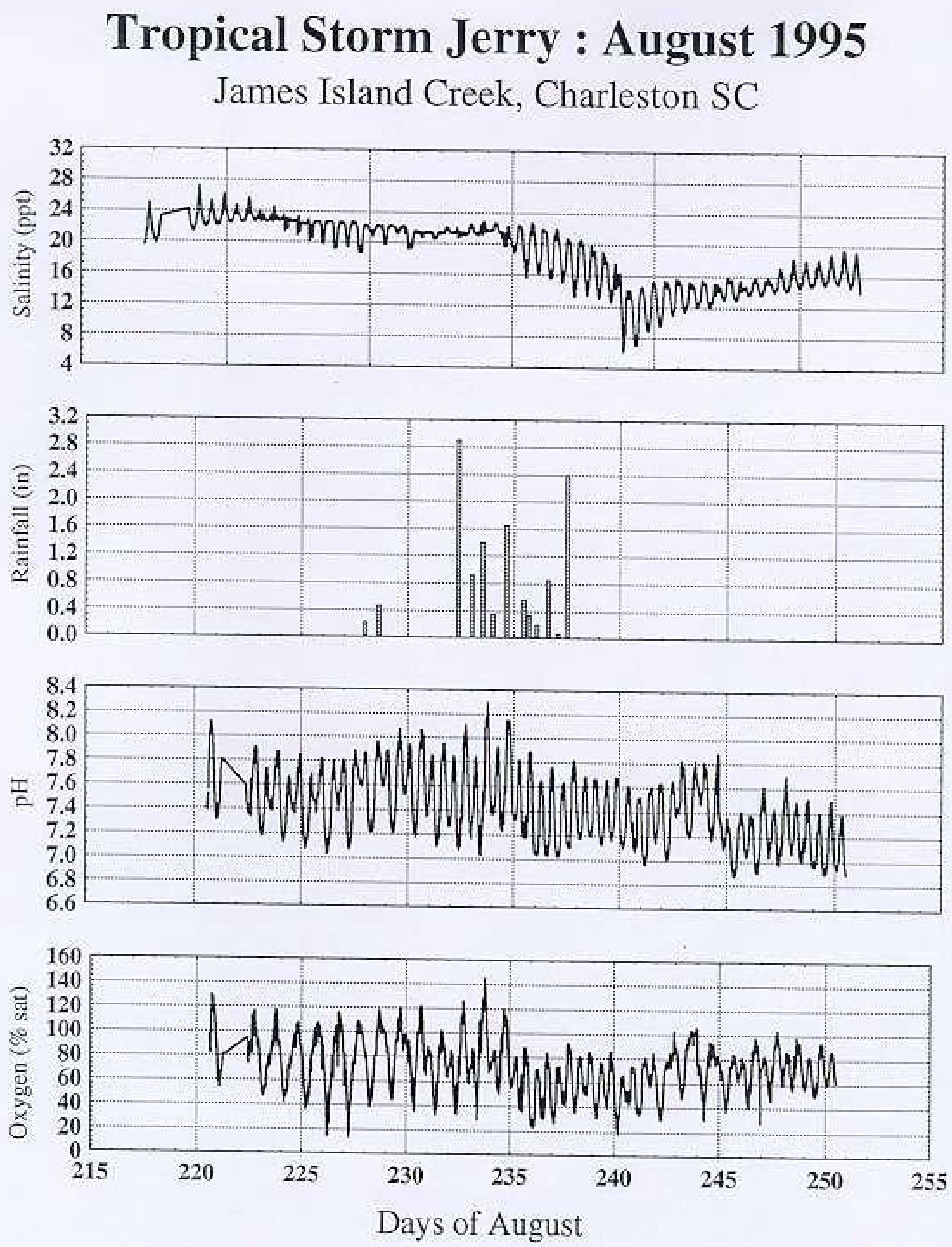

Tropical Storm Jerry : August 1995
James Island Creek, Charleston SC
Salinity (ppt)
32
28
24
20
16
12
8
4
Rainfall (in)
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
pH
8.4
8.2
8.0
7.8
7.6
7.4
7.2
7.0
6.8
6.6
Oxygen (% sat)
160
140
120
100
80
60
40
20
0
215
220
225
230
235
240
245
250
255
Days of August

Figure 17.

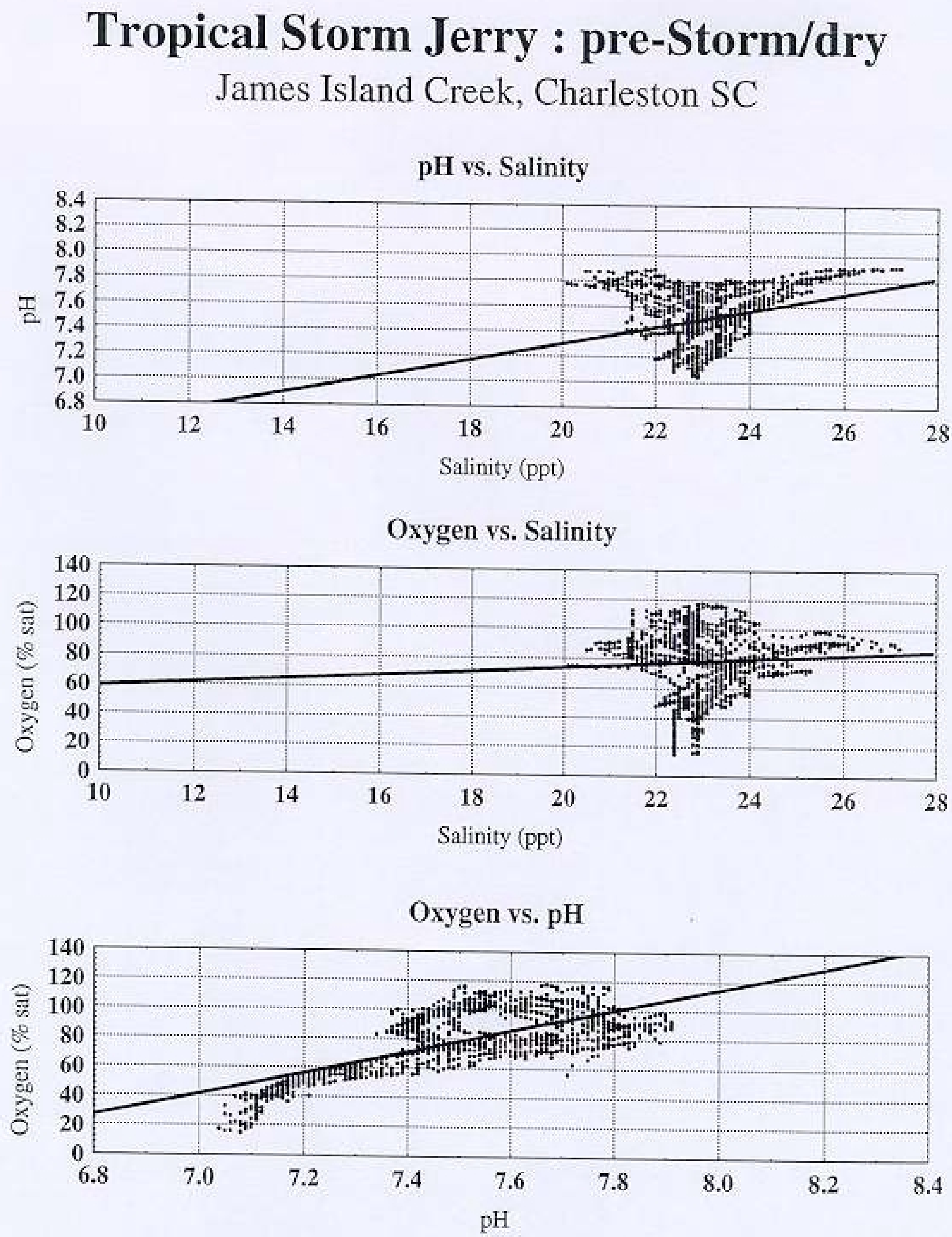

Tropical Storm Jerry : pre-Storm/dry
James Island Creek, Charleston SC
pH vs. Salinity
pH
8.4
8.2
8.0
7.8
7.6
7.4
7.2
7.0
6.8
10
12
14
16
18
20
22
24
26
28
Salinity (ppt)
Oxygen vs. Salinity
Oxygen (% sat)
140
120
100
80
60
40
20
0
Salinity (ppt)
Oxygen vs. pH
6.8
7.0
7.2
7.4
7.6
7.8
8.0
8.2
8.4
pH

Figure 18.

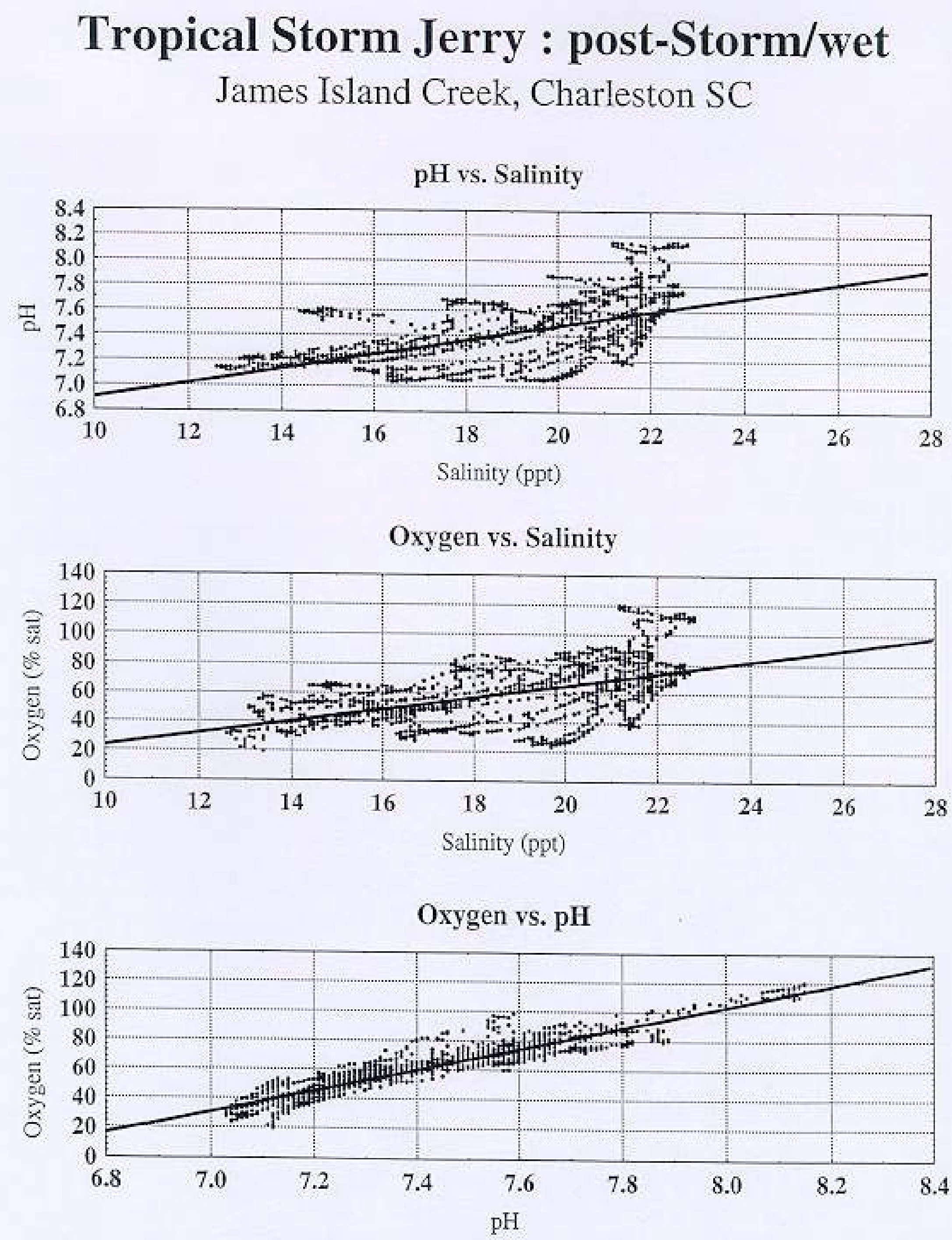


Figure 19.

Spectral analysis of the pre-storm data (Fig. 20 and 21) shows revealed a single broad peak in wavelength for salinity, a double peak in spectral density at

12 and 20 hours for pH, and a single peak centered at 24 hours for dissolved oxygen. Under drought conditions it appears that the dominant forcing function occurs with a 20 to 24 hour periodicity, perhaps the solar cycle.

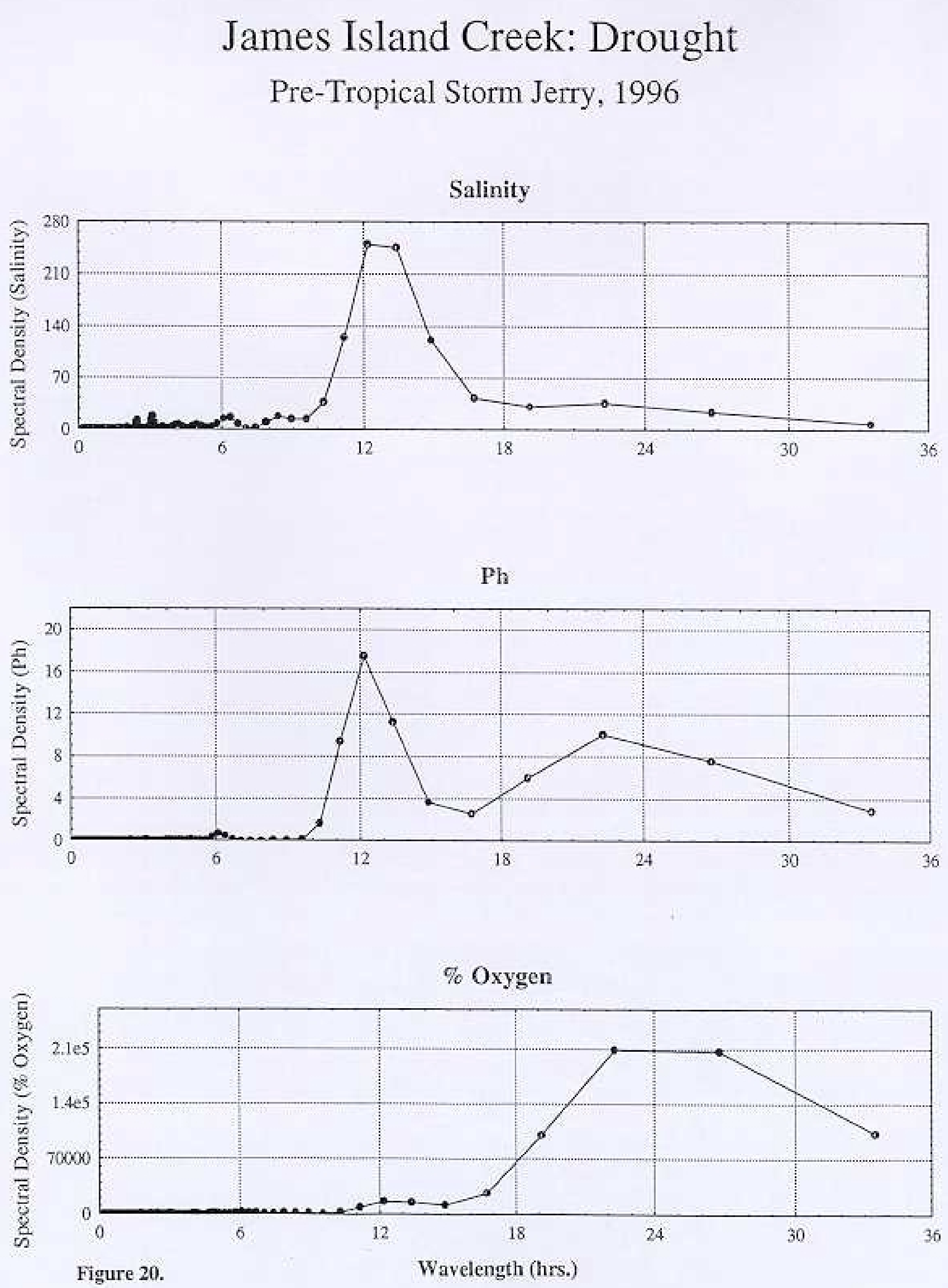
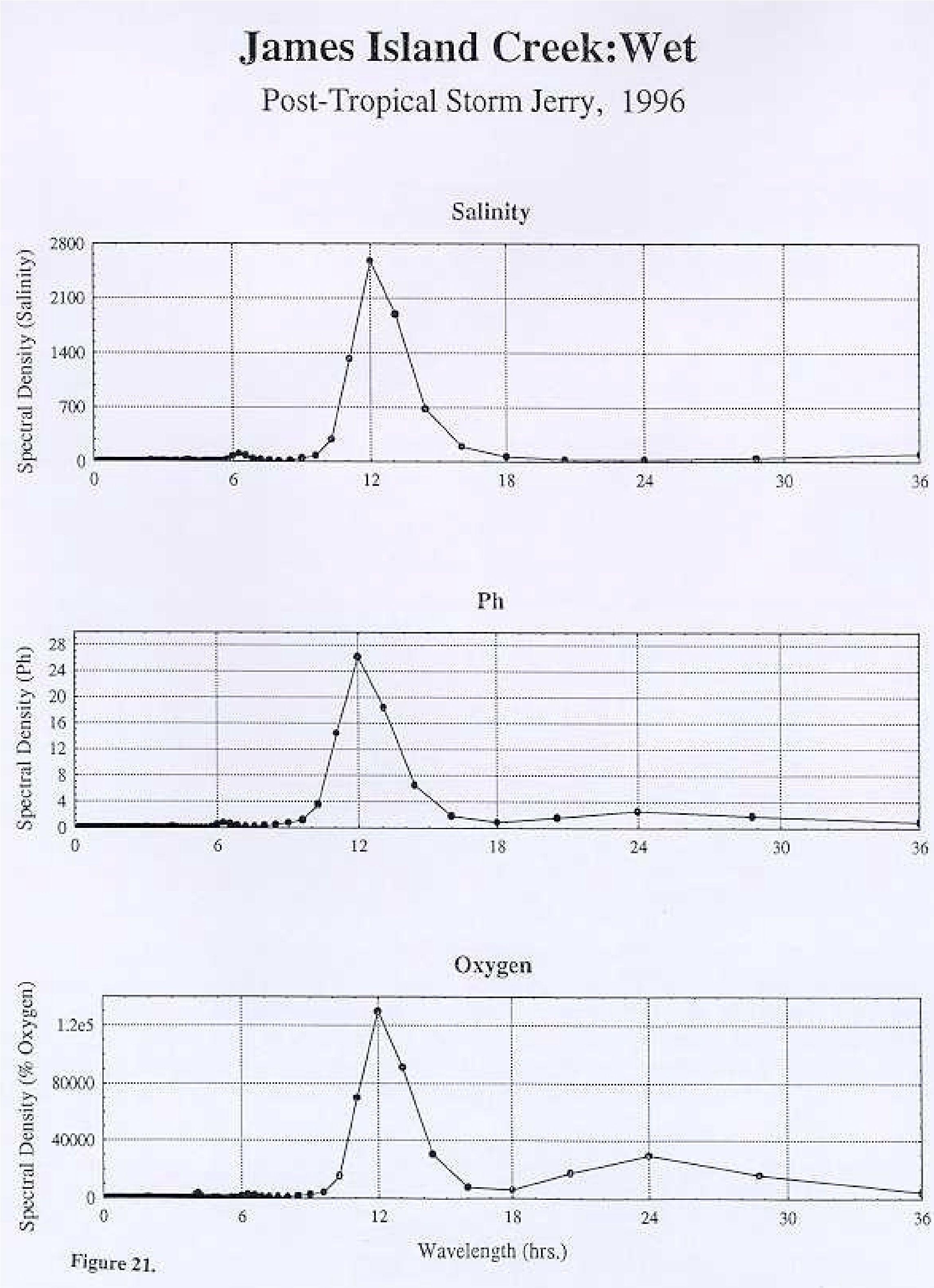


Figure 20.



Two days after the rains began (day 233) , a strong tidal signal reappeared in the salinity recording and pH and oxygen values dropped.

Spectral analysis indicated that salinity, pH and oxygen spectral densities shifted towards periodicity centered on a 12 hour wavelength. Thus, before the storm, creek metabolism displayed a dominant spectral density at 24 hours, which quickly reverted to the more commonly seen 12 hour, tidally linked signal. The input of storm water resulted in a lowering of estuarine oxygen concentration and apparently caused the creek to shift its “metabolic clock”, perhaps revealing a previously unknown linkage between weather and the patterns of variability of estuarine creeks.

Nutrients

Discrete nutrient sampling carried out at James Island Creek and Toomer Creek at hourly intervals during tidal cycles showed the data were highly variable. Nitrate ranged from .02 to .14 $mg \cdot l^{-1}$, nitrite .001 to .102 $mg \cdot l^{-1}$, phosphate .07 to 3.16 $mg \cdot l^{-1}$, and silicate .87 to 4.43 $mg \cdot l^{-1}$ (Appendix 2.). While there is no significant correlation between nutrients and salinity, the range of a variable increases with salinity, suggesting that the mainstream waters of Charleston Harbor, and the Wando River may be sources of nutrients for these estuarine creeks (Fig. 22.). An examination of the data with respect to tidal height suggests that nutrient levels appear higher at low tide on some occasions. While these observations reinforce the dual gradient concept that both mainstem and source waters contribute to the distribution of materials in estuaries, more data are needed to address this question (Appendix 3.).

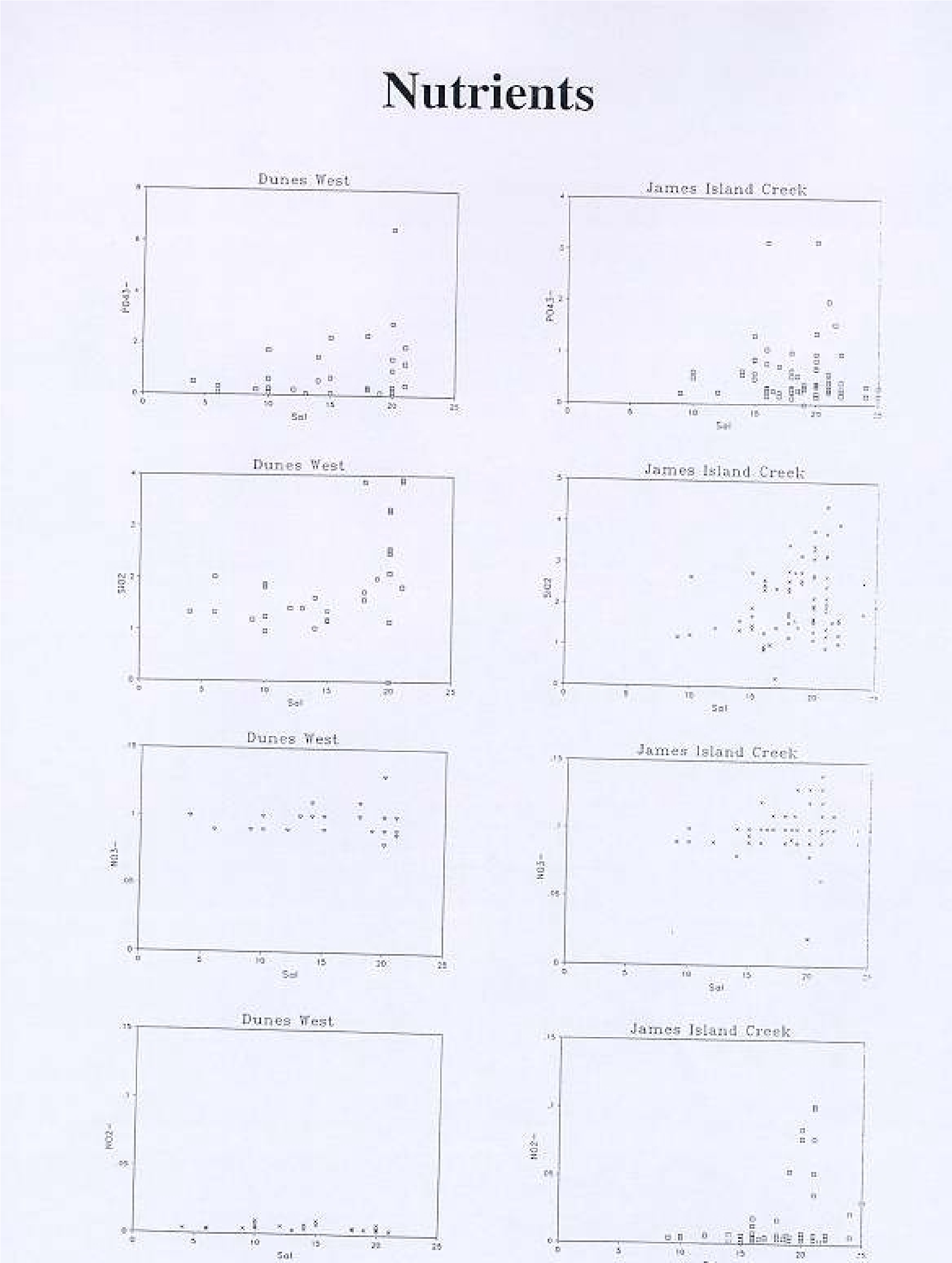


Figure 22.

During one sampling period (19 July) at Toomer Creek, a large thunderstorm dropped approximately one inch of rain in an hour period. Nutrient levels spiked a few hours later perhaps due to leaching or elevated nutrients in the rainwater itself. The rapidity at which the levels spiked illustrates the speed that water moves through the sandy soils of a forested ecosystem and into the estuarine waters.

Biological Oxygen Demand

Summer 1994 was marked by one of the wettest, and most continuously wet, summers on record. We had hoped to carry out a series of pre/post rain experimental incubations, but rainfall patterns were such that it almost never dried out. Under these abnormal conditions, a single series of experimental incubations on water column respiration rates before and after rain events were completed. The data, although variable, demonstrated that the water column respiration rates increase significantly after a rain event (Fig. 23). However, there appears to be threshold below which the rainfall does not trigger a short term oxygen depletion event and higher rainfall amounts apparently washout the system through “overflooding”.

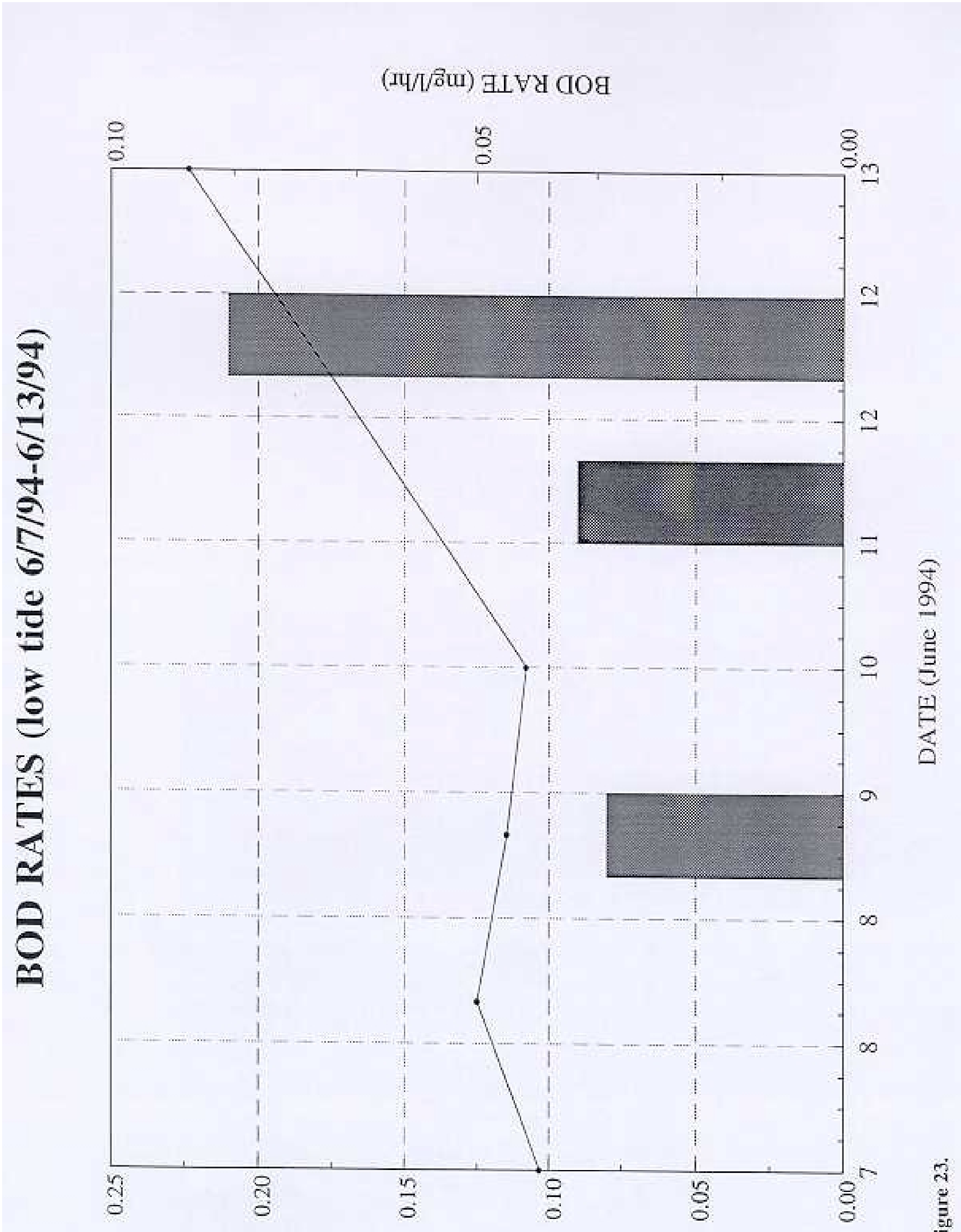

BOD RATES (low tide 6/7/94-6/13/94)
BOD RATE (mg/l/hr)
0.10
0.05
0.00
Rain (inches)
0.25
0.20
0.15
0.10
0.05
0.00
7
8
8
9
10
11
12
12
13
DATE (June 1994)

Figure 23.

Discussion

As the tide floods and ebbs in estuarine creeks, friction with the sides and bottom of the estuary causes tidal waves and currents which mix the water column (Pelegri , 1988; Blumberg and Goodrich, 1990; Sherwood et al., 1990; Simpson et al., 1990; Uncles and Stephens, 1990; Uncles and Stephens, l990b). These creeks are relatively narrow and while their maximum depths may approach 10 meters in a few areas, they are relatively shallow in relations to the fluctuation in tidal height which can be in excess of 1.8 meters. Bridges, boats and anything in the water can create turbulence and mix the water column (Kuo and Neilson, 1987; Schroeder et al., 1990). Thus, the overturn of the tides probably mixes the estuarine creeks from top-to-bottom during each tidal cycle well enough so that a measurement made at a single point is representative of the creek in general. With this in mind , the general descriptive summary statistics for the entire sampling periods do not reveal any dramatic differences between the two creeks, even though one has a highly urbanized watershed and the other was principally forested.

However, the analysis of the high frequency data suggests that these two creeks differ in their response to periods of intense rainfall; perturbations caused by rainfall seems to have a larger impact on creeks with urbanized watersheds. James Island Creek with its urbanized watershed has a weaker high frequency periodic signal. This may result from the urbanized watershed being more channeled; with increased sheet runoff, which tends to reflect the periodicity of the rainfall while partially disrupting or masking the tidal signal. Toomer Creek, on the other hand, reacts to a rainstorm as though it were a string which, if suddenly plucked vibrates back to its central frequency; the rainfall is intercepted by the land and released into the estuary through groundwater seepage.

Runoff from a storm enters the urbanized estuary quickly from roadways, lawns, and storm drains generating a signal with increased variance and range. Rainfall events in the less developed watershed appear to be "ecologically damped" as the range and amplitude of variation after a rainfall is considerably less. Salinity changes are not as sharp, and pH and O_2 are less variant after rainstorms of equivalent magnitude. One explanation for these differences appears to be linked to the alterations that occur in the hydrodynamics of urbanized watersheds. The early stages of urbanization tend to dramatically increase rates of soil erosion, but once houses are built and the disturbance ceases, urban lands may have very low rates of erosion (Goudie, 1990). Later, because urbanization increases the surface of impermeable substrates (roads, roofs, driveways) the runoff from flood rains occurs sooner and may be greater than in forested systems. Runoff tends to become more channeled with the construction of roads and drainage systems which results in peak discharges occurring sooner and at higher rates along a more direct pathway into the estuary (Hopkinson and Vallino, 1995).

In forested watersheds, the canopy intercepts rainfall which reduces the erosive effect of rain. Additionally, humus on the forest floor increases the permeability of the soil. Forest soils tend to be less compact than urban soils because roots and soil fauna form microchannels for water to infiltrate into the ground. These same features tend to conserve sediment loss, which can be 10 to 100 times higher in small urbanizing areas and developed or industrialized areas (Correll et al., 1992; Hopkinson and Vallino, 1995).

This study produced a detailed record of variability of two estuarine creeks, one forested, the other urbanized. The two differed little in their annual variability, but there were characteristic changes resulting from storms that suggest range and urban development alters the patterns of natural variability during storm events making conditions more unpredictable (higher variability) and, at the same time, increasing the biological oxygen demand through increased water column respiration rates resulting from increased microbial activity. James Island Creek showed a deeper and more immediate drop in oxygen concentration as a result of rainstorms. Such a drop may be caused by increases in water column respiration, demonstrated experimentally for a different storm. The concomitant changes in pH and O_2 are hypothesized to result from a loss or organic carbon which, once imported into the estuary, cause an increase in biological oxygen demand. While a macroscale event such as Hurricane Hugo, can have dramatic effects on oxygen content, urbanization, and development in general, may apply a chronic stress over a period of years (Howarth, et al, 1991). Such chronic stress may alter the natural selective forces on the creek community which may effect primary production, community structure and/or biodiversity. While it is clear that much more work needs to be done to clarify the dynamics of short term oxygen depletion (STODE effect), the perturbations caused by rainfall seem to have a larger impact on urbanized watersheds than in the less developed ones. With this in mind, thought needs to be given towards denying rainwater unhindered access to estuarine creeks. The urban lawn could be allowed to revert to urban forest landscapes, buffer strips could be implemented to trap the sediments and organic carbon transported by sheet flow, Stormwater drainage systems could be designed for new and existing developments that better mimic the path of runoff in natural systems.

Acknowledgments

Numerous College of Charleston students were employed during this period. Special thanks are due to those who worked in the field and laboratory, on both wet and dry aspects of this research project: graduate students Shirley Conner, Allison King, Michael Taylor, and undergraduate assistants Heidi Baker, Jerry Chapman, Eric Marriot, Paul Martin, Dan Pescio, Dan Russ, and Laura Schrum. George Nelson and Michael Brill assisted in the preparation of imagery and figures.

Literature Cited

Abel, M. B., Pennington, P. (1991) Estuarine Phytoplankton Ecology of the Charleston Harbor Estuary: Short-Term Oxygen Depletion Events. Bachelor's Essay BIO 499, College of Charleston.

Boynton, alter, J. T. Hollibaugh, D. Jay, M. Kemp, J. Kremer, C. Simenstad, S. V. Smith, and I. Valiea. 1992. Understanding changes in coastal environments: the LMER Program. Transactions of the American Geophysical Union. 73(45):481-485.

Correll, D., T.E. Jordan, D. Weller 1992. Nutrient flux in a landscape: effects of coastal land use and terrestrial community mosaic on nutrient transport to coastal waters. Estuaries Vol 15, No. 4. p. 431-442.

Day, J. W., Jr., Hall, C.A.S., Kemp, W. M., Yanez-Arancibia, A. (1989) Estuarine Ecology. John Wiley & Sons, New York.

Dustan, P., Pennington, P., M.B Abel, and N. Yoon 1991. Short term oxygen depletion events after Hurricane Hugo. The Oceanography Society 3rd Annual meeting, St. Petersburg, Fl.

Goudie, A. 1990. The Human Impact on the Natural Environment. MIT Press (Cambridge, Mass.) 388 pp.

Hopkinson, C.S. Jr. , J. Vallino 1995. The relationships among man's activities in watersheds and estuaries: a model of runoff effects on patterns of estuarine community metabolism. Estuaries Vol 18, No. 4. p. 596-621.

Howarth, R. W., Fruci, J. R., Sherman, D. (1991) Inputs of Sediment and Carbon to an Estuarine Ecosystem: Influence of Land Use. Ecological Applications 1:27-39

Likens, G.E., Bormann, F.H., Pierce, R.S., Eaton, J.S. (1985) The Hubbard Brook Valley An Ecosystem Approach to Aquatic Ecology: Mirror Lake and its Environment. Springer-Verlag, New York

McGiff, E.C. The Effects of Urbanization on Water Quality. J. Environ. Geol. 1(1) 86:89.

Parsons, T.R., Maita, Y., Lalli, C.M. (1984) A Manual of Chemical and Biological Methods for Seawater Analysis. Pergamon, New York.

Portnoy, J.W. (1991) Summer Oxygen Depletion in a Diked New England Estuary. Estuaries, 14:122-129.

Literature Cited (cont.)

Valiela, I, K. Forman, M. LaMontagne, D. Hersh, J. Costa, P. Peckol, B. DeMeo-Anderson, C. D'Avanzo, M. Babione, C. Sham, J. Brawley, K. Lajtha 1992. Couplings of watersheds and coastal waters: sources and consequences of nutrient enrichment in Waquoit Bay, Massachusetts. Estuaries Vol 15, No. 4. p. 443-457

List of Figures.

List of Figures (cont).

Appendix 1. Variation in water quality by month:
James Island Creek and Toomer Creek.

*Available upon request from SC DHEC-OCRM, 1362 McMillan Avenue, Charleston, SC 29405

Appendix 2. Dissolved nutrients for James Island Creek (JIC).

	DATE	TIME	NO3-	NO2-	PO43-	SiO2	SAL	TIDE	REMARKS
JIC	6/4/93	730	0.10	0.007	0.25	1.28	21	4.7	
		835	0.11	0.006	0.31	1.62	22	5.2	
		935	0.10	0.004	0.28	1.64	19	5.0	
		1035	0.10	0.003	1.56	1.62	22	4.1	
		1135	0.10	0.006	0.44	2.48	21	2.7	
		1240	0.09	0.005	0.55	2.82	19	1.1	
		1340	0.10	0.004	0.30	3.25	21	-0.1	
		1445	0.09	0.005	0.54	3.48	18	-0.5	
		1545	0.10	0.004	0.34	3.76	21	0.1	
		1710	0.10	0.005	0.99	4.00	22	2.0	
		1750	0.11	0.007	0.26	1.48	19	3.1	
		1905	0.11	0.005	0.30	1.23	18	4.9	
		2005	0.11	0.005	0.16	1.46	17	6.1	
		mean	0.10	0.01	0.48	2.32	20	2.9	
		stdev	0.01	0.00	0.39	1.02	2	2.3	
JIC	6/14	300	0.10	0.003	0.33	0.92	16	4.2	
		400	0.10	0.004	0.26	1.04	17	4.5	
		500	0.10	0.005	0.24	0.22	17	4.4	
		600	0.10	0.004	0.26	2.44	18	3.8	
		700	0.10	0.003	0.69	2.70	20	2.9	
		800	0.08	0.003	0.37	3.16	20	1.9	
		900	0.09	0.003	0.39	2.55	19	1.1	
		1000	0.08	0.005	0.37	2.76	20	0.6	
		1100	0.09	0.004	0.28	1.45	21	0.7	
		1200	0.12	0.004	0.31	2.38	16	1.4	
		1300	0.10	0.005	0.74	2.42	17	2.4	
		1400	0.09	0.005	0.66	2.35	18	3.5	
		1500	0.10	0.005	0.16	2.49	16	4.4	
		mean	0.10	0.004	0.39	2.07	18	2.7	
		stdev	0.01	0.00	0.19	0.87	2	1.5	

Appendix 2. (cont.). Dissolved nutrients for James Island Creek (JIC).

	DATE	TIME	NO3-	NO2-	PO43-	SiO2	SAL	TIDE	REMARKS
JIC	6/15	400	0.09	0.006	3.14	0.93	16	4.2	
		500	0.02	0.008	1.38	2.01	20	4.5	
		600	0.10	0.007	0.13	2.60	18	4.3	
		700	0.10	0.006	0.71	1.38	20	3.6	
		800	0.10	0.004	3.16	3.36	20	2.7	
		900	0.09	0.004	1.38	3.46	20	1.7	
		1000	0.09	0.005	1.01	2.84	18	0.9	
		1100	0.10	0.006	0.87	2.79	15	0.4	
		1200	0.10	0.006	0.49	1.42	15	0.6	
		1300	0.10	0.008	0.79	1.00	16	1.5	
		1400	0.10	0.006	0.00	2.82	19	2.7	
		1500	0.10	0.006	0.21	1.99	20	3.8	
		1600	0.10	0.005	0.15	1.70	20	4.7	
		mean	0.09	0.01	1.03	2.18	18	2.7	
		stdev	0.02	0.00	1.04	0.86	2	1.6	
JIC	6/19	810	0.10	0.005	0.26	1.09	22	4.7	
		915	0.10	0.004	0.18	1.31	22	4.5	
		1015	0.10	0.008	0.44	1.69	22	3.7	
		1115	0.09	0.004	0.50	2.71	21	2.6	
		1215	0.09	0.004	0.51	2.68	10	1.3	
		1315	0.09	0.005	0.40	2.19	20	0.3	
		1415	0.09	0.005	0.41	3.82	20	-0.2	
		1515	0.06	0.003	0.33	4.43	21	0.2	
		1615	0.10	0.004	0.34	3.22	19	1.4	
		1715	0.09	0.003	0.60	1.94	15	2.9	
		1815	0.10	0.004	1.33	1.74	15	4.4	
		1915	0.10	0.001	0.86	1.51	15	5.5	
		2015	0.08	0.002	0.65	1.38	14	6.2	
		mean	0.09	0.00	0.52	2.28	16	4.1	
		stdev	0.01	0.00	0.30	1.03	2	2.0	

Appendix 2. (cont.). Dissolved nutrients for James Island Creek (JIC).

	DATE	TIME	NO3-	NO2-	PO43-	SiO2	SAL	TIDE	REMARKS
JIC	8/5	915	0.10	0.031	0.33	2.00	25	4.7	
		1000	0.11	0.032	0.185	1.04	25	5.1	
		1100	0.14	0.102	0.39	2.07	21	5.3	
		1200	0.12	0.053	0.25	0.96	21	4.9	
		1310	0.10	0.008	0.36	1.60	20	3.8	
		mean	0.11	0.05	0.30	1.53	22	4.8	
		stdev	0.02	0.04	0.08	0.52	2	0.6	
JIC	8/11	810	0.11	0.018	0.34	1.83	18	0.9	
		900	0.10	0.014	1.07	2.61	16	0.8	
		1000	0.10	0.019	0.26	1.32	16	1.2	
		1100	0.11	0.037	0.33	3.19	21	2.1	
		1200	0.13	0.054	0.30	2.62	19	3.2	
		1410	0.13	0.101	2.00	1.98	21	5.0	
		mean	0.11	0.04	0.72	2.26	19	2.5	
		stdev	0.01	0.03	0.70	0.67	3	1.7	

Appendix 2. (cont.). Dissolved nutrient values for Toomer Creek (TC)

SITE	DATE	TIME	NO3-	NO2-	PO43-	SiO2	SAL	TIDE	REMARKS
TC	7/19	930	0.10	0.005	0.20	2.57	20	6.4	
		1030	0.09	0.003	0.20	2.54	20	6.3	
		1130	0.09	0.003	0.05	N/A	20	5.3	
		1230	0.08	0.004	2.82	3.31	20	3.6	
		1330	0.09	0.012	1.25	3.89	21	1.6	1530-1630
		1430	0.09	0.003	0.40	3.92	21	0.0	(1" rain)
		1530	0.13	0.004	1.43	2.57	20	-0.6	
		1630	0.10	0.004	2.35	3.87	18	0.0	
		1830	0.10	0.008	6.50	3.35	20	3.4	
		1930	0.10	0.003	1.91	1.85	21	5.2	
		2030	0.08	0.003	0.15	2.49	20	6.7	
		mean	0.10	0.00	1.57	2.76	20	3.0	
		stdev	0.01	0.00	1.90	1.15	1	3.2	
TC	8/4	900	0.11	0.004	1.50	1.03	14	5.0	
		1000	0.10	0.007	0.69	1.37	15	5.9	
		1100	0.09	0.004	0.11	2.00	19	6.5	
		1200	0.10	0.003	0.07	1.42	13	6.4	sprinkling
		1300	0.10	0.004	0.50	1.34	4	5.4	since 1400
		1400	0.09	0.004	0.10	1.33	6	3.8	hard rain fo
		1600	0.09	0.005	0.34	2.11	20	0.7	35 minutes
		1700	0.10	0.010	0.27	1.84	10	0.4	
		1900	0.10	0.007	0.10	0.97	10	2.3	
		mean	0.10	0.01	0.41	1.49	10	2.5	
		stdev	0.01	0.00	0.46	0.40	6	2.1	
TC	8/5	930	0.10	0.005	0.98	1.17	20	4.9	
		1030	0.10	0.007	0.57	1.62	14	5.9	
		1130	0.09	0.006	0.23	1.42	12	6.4	
		1230	0.09	0.004	0.21	1.20	9	6.4	
		1330	0.10	0.005	0.63	1.26	10	5.6	
		1430	0.10	0.005	0.24	1.75	18	4.0	
		1530	0.11	0.004	0.32	1.59	18	2.4	
		mean	0.10	0.01	0.45	1.43	13	5.0	
		stdev	0.01	0.00	0.29	0.23	4	1.8	

Appendix 2. (cont.). Dissolved nutrient values for Toomer Creek (TC)

	DATE	TIME	NO3-	NO2-	PO43-	SiO2	SAL	TIDE	REMARKS
TC	8/11	900	0.09	0.003	0.33	2.03	6	1.1	
		1100	0.09	0.004	1.75	1.88	10	1.7	
		1300	0.09	0.010	0.10	1.18	15	4.1	
		1400	0.10	0.007	2.27	1.20	15	5.2	
		mean	0.09	0.01	1.11	1.57	12	3.0	
		stdev	0.00	0.00	1.06	0.45	4	1.9	

Appendix 3. Dissolved nutrient content in relation to tidal height:
James Island Creek (JIC) and Toomer Creek (TC).

*Available upon request from SC DHEC-OCRM, 1362 McMillan Avenue, Charleston, SC 29405